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Shake and Break:
The HESSI Overtest Mishap

On March 21, 2000, the High Energy Solar Spectroscopic Imager (HESSI) spacecraft was subjected to a series of vibration tests at the NASA/Caltech Jet Propulsion Laboratory (JPL) as a part of its flight certification program. A major overtest occurred during the "sine-burst" structural qualification test that caused significant structural damage to the spacecraft. "Stiction" (static friction) between the granite reaction mass and the slip plate of the shaker test system, combined with a self-check that had been performed at very low force input levels, resulted in the calculation of an inappropriate drive signal. The resulting pulse was ten times higher in amplitude than expected, causing the overtest.

This photo was taken at JPL shortly before the vibration test anomaly which damaged the spacecraft

Background: HESSI System-Level Test

The spacecraft. HESSI (later renamed the Reuven Ramaty High Energy Solar Spectroscopic Imager, or RHESSI) is the sixth mission in the line of NASA Small Explorer missions (also known as SMEX). Launched on February 5, 2002, its primary mission is to explore the basic physics of particle acceleration and explosive energy release in solar flares. Instead of mirrors and lenses, solar imaging is based on a Fourier-transform technique using a set of nine Rotational Modulation Collimators (RMCs). The RMCs are held in known, fixed positions by a tubular telescope structure that forms the bulk of the spacecraft. With the spacecraft rotating at ~15 rpm, the rotating RMCs time-modulate the solar flux arriving at the detectors. A set of four, fixed solar panels is designed to provide enough gyroscopic moment to stabilize rotation about the solar vector. This largely eliminates the need for attitude control. The HESSI project was managed by the Space Sciences Laboratory of the University of California (UC), Berkeley, with the spacecraft bus manufactured by Spectrum Astro, Inc. The payload was high altitude air-launched to orbit by a Pegasus winged launch vehicle.

Dynamic testing. Environmental testing poses risks to spaceflight hardware because the hardware is intentionally stressed to the maximum expected environment, plus a margin. System-level testing warrants extra care because it occurs after the flight system and instruments have been fully integrated-- when any damage is difficult to repair. HESSI was the first SMEX project to be PI-led, and the Principal Investigator at UC Berkeley elected to have JPL perform system-level vibration testing.

Vibration testing of the spacecraft certifies the flight hardware to the environmental loading conditions experienced during the ground handling, captive carry, and

> **"Shake and Break"**
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> **Structural damage to the spacecraft exceeding $1 million**
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> **Proximate cause:**
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> - Mechanical binding between the slip table and the granite mass
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> **Incident Context:**
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> - Aging NASA industrial facilities and critical equipment pose a substantial risk to the development of high value, one-of-a-kind products

launch mission phases. A computer controls how hard the spacecraft is shaken, and accelerometers measure the response of the spacecraft to the shaking. Three types of vibration tests were mandated for HESSI:

1. To characterize the spacecraft, a low-amplitude sine survey assesses the fidelity of the analytical model and identifies the major structural resonances of the spacecraft.
2. A random qualification test accounts for the effects of structurally transmitted vibrations during captive carry and launch.
3. A sine-burst test qualifies the spacecraft for structural integrity. Quasi-static loading is applied to the structure via an electro-dynamic exciter (shaker).

Testing of the spacecraft primary structure is a priority because it is one of the few subsystems that is a single point failure during flight. Elements of this subsystem include structural members, their connections, and their interfaces with all major spacecraft assemblies. The main purpose of the structural loads test (#3 above) is to verify, with margin, the structural integrity of all primary structure for the anticipated mission dynamics and loads environments.

The sine-burst test method was chosen for HESSI because it could be performed in conjunction with the vibration qualification test, adding negligible schedule and cost to the test program. Alternative structural loads qualification tests have some practical drawbacks:

1. *Static loads* tests require complex test setups and sometimes take weeks to perform,
2. *Sine dwell* and *sine sweep* vibration tests induce excessive fatigue cycles in the structure and, if the input frequency is near hardware resonances, excessive resonance buildup, and
3. *Centrifuge* test facilities are less common among spacecraft developers and are limited in the weight of the test article they can accommodate.

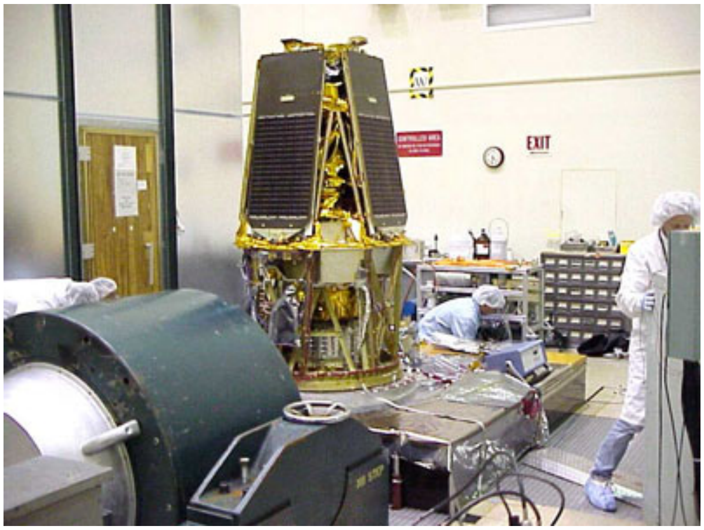
Test Safeguards. Vibration testing can potentially overstress and damage the test article if the test facility and the test team does not exercise appropriate rigor in their test procedures, facility maintenance, and personnel training. Sine burst testing can be more susceptible to inadvertent overtest than other vibration tests because the sine burst tests are conducted open-loop; that is, because of the transient nature of the test input, they do not employ a closed-loop feedback to adjust the input vibration level real time. Test safeguards employed by JPL on sine-burst tests include:

- The test conductor rigorously follows a *test plan* that has been reviewed and approved by a dynamic environments engineer.
- *Test limits* are calculated based on the c.g. acceleration specification, and on reaction force measurements between the mounting structure and the test article, which represents the enabling technology to obtain accurate test loads.
- To reduce the risk to flight hardware, a shaker test is always rehearsed either as a bare shaker or by exciting a *mass simulator* (i.e., mass mockup) prior to installing the test article (i.e., flight system) on the shaker.

Test Setup. The HESSI spacecraft was brought to the JPL Environmental Test Laboratory and mounted to an adapter ring. The adapter was then mounted to the magnesium alloy slip table via an aluminum fixture plate in preparation for testing in the spacecraft's X-axis. Force gages were placed between the spacecraft adapter ring and the fixture plate to measure the force input to the spacecraft.

The spacecraft adapter ring and aluminum fixture plate are clearly shown in a HESSI test configuration

A Ling Model A-249, JPL's largest shaker, was attached to the slip table to provide lateral excitation. The shaker and granite mass were mounted directly to an isolated floor section. A thin oil film separated the slip plate from the granite reaction mass. (The granite serves as an isolator, preventing the vibration from being induced into the laboratory floor.)



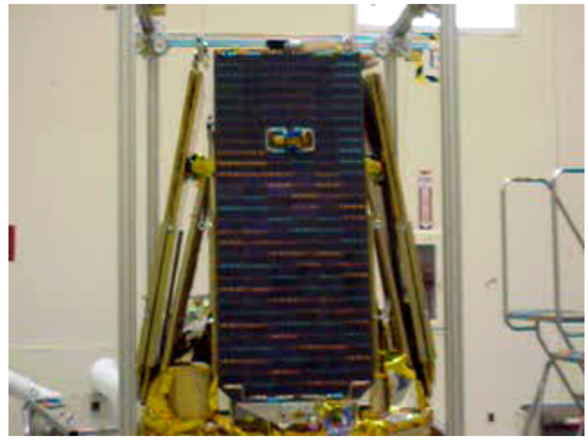
Preparing the Ling shaker and slip table for HESSI dynamic testing

The Mishap

Beginning on March 10, 2000, the HESSI spacecraft in flight configuration was subjected to a series of ten X-axis sine survey and random vibration test runs at JPL as a part of its flight certification program. The runs were completed without incident on JPL's Ling A-249 shaker table, which had been in use for well in excess of 40 years.

HESSI during an X-axis vibration test.

Test Run #11 on the evening of March 21 was a structural qualification test-- a sine-burst load test. A sine-burst test (Reference 2) subjects each orthogonal axis of the test item to between five and ten cycles of a sine wave whose peak is equivalent to the qualification load level. The test plan for Run #11 called for a sequence of six sine-bursts at one-quarter of full level (-12dB), followed by a single burst at one-half of full level (-6dB), and a single full level pulse after review of the input and responses. On the initial -12dB burst, an overtest of ten times the planned level (~20 G instead of 2 G) occurred, damaging the HESSI spacecraft solar arrays and structure.

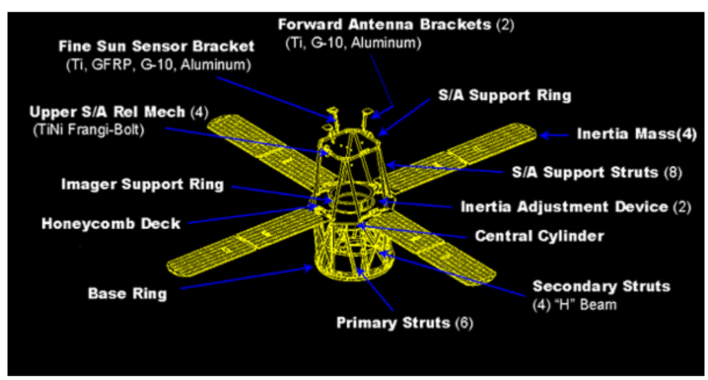


Video clip of solar array first motion during sine-burst overtest anomaly

Mishap Investigation

A HESSI Test Mishap Investigation Board (MIB) was formed in March 2000 in response to a NASA headquarters request. A report (Reference 1) was issued in May 2000.

Proximate (i.e., immediate) Cause. The MIB found that a mechanical failure in the shaker's support structure caused physical contact between a portion of the slip table and the granite mass. The resulting stiction caused the shaker system to present highly non-linear gain characteristics to the control system. Attempting to overcome the stiction, the controller calculated a very high forcing function that overshot the desired sine-burst amplitude and damaged major spacecraft structural elements.



HESSI structural elements

A pre-test self-check that emits a signal and measures the response had been performed, but at too low an amplitude to overcome the stiction in the system.

Contributing Factors. The MIB report identified the following contributing causes:

1. Misalignment caused the slip table to exhibit non-linear behavior—i.e., binding at low levels of force input.

2. The test team did not have existing knowledge that data were available to assess the quality of the transfer function calculated from the self-check prior to initiating the sine-burst test. Post-test review of the transfer function used to generate the shaker drive signal for the test and examination of the drive voltage indicated that the test setup was not operating as expected and that an overtest could occur.
3. A significant contributing factor to the mishap was the lack of a facility validation test using the sine-burst on the shaker table before the spacecraft was mounted. It is industry best practice to do a facility checkout with a simulated mass mockup before mounting a piece of critical hardware. Such an end-to-end validation test effectively calibrates the entire test setup.

Mishandling at JPL was not a contributing cause. (In this photo, the HESSI spacecraft is actually suspended from cables)

4. A further contributing factor to the mishap was a mechanical anomaly that occurred in the exciter system. The shaker appears to have shifted in its support cradle after being coupled to the slip table in preparation for this test. The shift is thought to have been caused by the breakage of the outer race of a main trunnion bearing. This resulted in a misalignment that brought one area of the slip plate into contact with the granite reaction mass creating a much larger frictional drag than normal.
5. An additional contributing factor to the mishap was the low amplitude of the pre-test self-check. If a higher amplitude self-check pulse had been used, the control software would have more closely approximated the system transfer function and increased the probability of detecting that stiction existed.
6. A contributing factor that could be added to the above is that, at some NASA facilities, older test equipment may have age-related failure modes unknown to the users.

Aftermath

The incident was designated a Class A mishap since the damage exceeded $1 million. The HESSI spacecraft was subsequently returned to the University of California, Berkeley, for repair and re-assembly, and the HESSI launch occurred 1-½ years later than planned.

A Corrective Action Notice (Reference 3) tracked JPL Environmental Test Laboratory action to repair the shaker and incorporate the lessons learned from the HESSI mishap. Recognizing the Agency-wide problem of aging facilities, NASA implemented a Critical Facilities Maintenance Assessment (Reference 4) at each of the NASA Centers that inventoried critical facilities and equipment, assessed their failure modes, and established Reliability Centered Maintenance (RCM) methods.

Discussion

1. The HESSI MIB Report (Reference 1, p. 21) states, "***Stiction caused by misalignment of the shaker and slip table was the root cause of this mishap***." Was stiction the root cause? (A root cause is an initiating cause of a causal chain that leads to an outcome.) What was the root cause?
2. The age of the Ling A-249 shaker table is unknown, but Ling had ceased making that model 40 years before the mishap. What does that tell you about the test equipment pedigree?
3. Why was no facility validation sine-burst test with a mass mockup conducted prior to mounting the flight hardware?
4. What could the project manager have done differently to prevent the mishap. [What if it had been a JPL project manager instead of the PI?]
5. What other responsible parties could have mitigated the risk. [CogE, dynamicist, test conductor, ETL manager, QA rep, safety rep. Unlike random vibration tests, JPL sine burst test setups during the HESSI period did not include an over-test protection scheme, such as a trip circuit based upon acceleration or displacement limits.]
6. What approaches are you using to assess and mitigate hazards to flight hardware in fabrication, handling, testing, system integration, retesting, launch, operation, etc.? [Max Adofo: At JPL, the requirement has traditionally been for CogEs to perform Interface FMEAs (I/F FMEAs) for EGSEs (but not for MGSEs),

with the intent of ensuring that no EGSE failure could propagate to damage or overstress parts in the flight hardware under test. More recently (MSL, SMAP projects, etc.), however, JPL Systems Safety (mainly Ron Welch) and Rob Manning have insisted on having CogEs (and JPL Contractors like Lockheed Martin) perform a so-called Functional FMECA (FFMECA/FFMEA) for MGSEs used for safety-critical flight hardware tests, MGSEs used on JCIs, and MGSEs used for eleventh-hour tests on flight hardware, assemblies, and flight sub-systems with long lead time parts/components that CANNOT and MUST NOT fail during such tests. The FFMECA requirement also covers MGSEs used on fully assembled (wet) spacecraft. The FFMECA covers both mechanical and electrical potential failures of the MGSE, including the MGSE's Electrical Control Box, with the goal of ensuring that there are no mechanical or electrical failures that can propagate to harm the hardware being tested. In that regard, FFMECAs have recently been performed for the JPL ETL's Spin Balance Table (used to measure the center of gravity, moment of inertia, and product of inertia of spacecraft descent stages, cruise stages, and the complete wet spacecraft), MMRTG Integration Cart and Lift/Turn-Over Fixture, the MSL Spacecraft Assembly Rotation Fixture (SCARF), and an RTG Heat Exchanger GSE. It needs to be mentioned that at some MSL test-prep meeting, where there was some push-back from certain quarters regarding the need for these special-case MGSE FFMECAs, Rob Manning invoked a new/recent high-level NASA requirement (at the time) to justify them. Guess you could contact Rob to obtain the particular NASA requirement.]

7. It has been estimated that JPL will lose one-half of its workforce over the next ten years due to retirement and turnover. How might that affect JPL's ability to safely conduct specialized engineering tasks like environmental testing? How should a project manager manage the risk of using less senior personnel?
8. How might JPL and your line organization disrupt the "Cycle of Forgetfulness," in which the widespread recognition of process flaws following a mishap fades over time?
9. What other lessons learned may be drawn from the incident that inform Lab-wide processes and/or affect your project?
10. In your experience, is there a relationship between cost-cutting approaches to project development and the potential for test mishaps and test errors?

References

1. Report on the High Energy Solar Spectroscopic Imager (HESSI) Test Mishap, HESSI Test Mishap Investigation Board, May 18, 2000. http://oce.jpl.nasa.gov/mib/HESSI-1.pdf
2. "Sine-Burst Load Test," NASA Preferred Reliability Practice No. PT-TE-1420, http://oce.jpl.nasa.gov/practices/1420.pdf
3. "HESSI Mishap - Lessons Learned," JPL Corrective Action Notice No. 1018, May 17, 2000.
4. "Critical Facilities Maintenance Assessment," Lesson Learned No. 1764, July 27, 2006 http://llis.nasa.gov/lesson/1764

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